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SUPERSONIC AERODYNAMIC HEATING TESTS ON A LIGHTWEIGHT EXTERNAL INSULATION SYSTEM FOR LIQUID-HYDROGEN TANKS OF BOOST VEHICLES

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Lewis Research Center
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SUMMARY

A development program on a lightweight, sealed-foam, constrictive-wrapped external insulation system for liquid-hydrogen tanks on boost vehicles has resulted in a very promising system design. Aerodynamic heating tests have been performed previously on this system at subsonic conditions and transonic-supersonic conditions up to Mach 2 to simulate part of an assumed typical launch trajectory. The current investigation extended the environmental testing conditions to Mach 3.5 and free-stream total temperatures up to about 650° F. The free-stream dynamic pressures were between 500 and 620 pounds per square foot. These environmental conditions resulted in insulation surface temperatures that approximate those encountered at these Mach numbers during the launch trajectory. Because of the test facility operating characteristics, the time of exposure at the test conditions was about 2.4 hours compared with about 3 minutes for the launch trajectory.

In general, the insulation system successfully withstood the effects of the supersonic aerodynamic heating tests. Results of this and other aerodynamic heating investigations on the insulation system indicate that the system appears to be satisfactory for withstanding the aerodynamic environment of a typical launch trajectory.

INTRODUCTION

Insulation systems for liquid-hydrogen tanks of boost vehicles must provide adequate thermal protection for both ground hold and the launch trajectory. Of prime importance for an exposed external insulation system is retention of the structural integrity of the insulation for that part of the launch trajectory during which high aerodynamic heating rates and high dynamic pressures are encountered. The development of a lightweight, sealed-foam, constrictive-wrapped external insulation system to satisfy this requirement is described in detail in reference 1. Effects of aerodynamic heating in a subsonic exhaust stream of a turbojet engine and in a transonic-supersonic wind tunnel up to Mach 2 on specimens from several stages of development on this insulation system are described in chapter VI of this reference.

The purpose of the present series of tests was to extend the aerodynamic heating investigation on the final and most successful configurations of this insulation system to more critical conditions of free-stream Mach number and insulation surface temperature than were encountered in previous testing.

As pointed out in chapter II of reference 1, two of the most important environmental parameters associated with the launch trajectory are surface temperature and dynamic pressure imposed on the insulation. The maximum values of these parameters for the launch trajectory assumed in reference 1 were about 650° F and 860 pounds per square foot, respectively. However, the maximum values of these parameters did not occur simultaneously. The peak pressure occurred early in the trajectory when the surface temperature was only 140° F; the peak temperature occurred later at higher altitude where the dynamic pressure was only about 150 pounds per square foot.

In previous testing, specimens of the insulation system have been subjected to simultaneous conditions of surface temperatures as high as 615° F and dynamic pressures as high as 685 pounds per square foot in the subsonic environment of the engine exhaust stream and to surface temperatures as high as 212° F and dynamic pressures as high as 1306 pounds per square foot at Mach 2 in the supersonic environment of the wind tunnel. The test specimens successfully withstood these environmental conditions for time periods representative of the launch trajectory in the case of the subsonic tests and for time periods greatly exceeding those of the launch trajectory in the case of the supersonic tests.

The current series of tests were conducted in the Lewis Research Center 10- by 10-foot supersonic wind tunnel using the same test specimens that had been used previously for the supersonic tests reported in reference 1. During these tests, environmental conditions approximating those encountered over a portion of the assumed launch trajectory were imposed on these specimens. These conditions were insulation surface temperatures from 55° to 516° F, dynamic pressures from 507 to 620 pounds per square foot and free-stream Mach numbers from 2.04 to 3.37. As was the case for the tests of reference 1, the specimens were mounted on a liquid-nitrogen-filled model tank and the time of testing greatly exceeded that associated with the assumed launch trajectory.

APPARATUS AND PROCEDURE

Model Tank

A cross-sectional schematic diagram of the insulated model tank used for these supersonic aerodynamic heating tests is shown in figure 1. This same bi-convex tank was used for the transonic-supersonic aerodynamic heating tests of reference 1. The outside dimensions of the insulated tank were 3 feet wide, 5 feet long, and about 7.5 inches high. The radius of curvature of the sides of the tank was 60 inches. This dimension matched the radius of the Centaur vehicle that was used as a basis for the insulation system design in reference 1. Corkboard insulation of the same thickness as the test specimens was used on the small-radius edges of the tank to withstand the large crushing loads generated at reduced radius by tensioned filament wrap, which is a component of the insulation system. The tank ends were insulated with corkboard. An aerodynamic fairing of fiberglass-reinforced plastic was attached to the forward end of the tank.

Test Specimens

Two specimens of the insulation system (shown schematically in fig. 2) were investigated during the supersonic aerodynamic heating tests described herein. The configurations studied were the most promising of those developed in the course of the aerodynamic heating tests of reference 1. The present investigation used the same test specimens (7 and 8) that were used in the transonic-supersonic aerodynamic heating tests reported in chapter VI of reference 1. The specimen designations of reference 1 will be used in the present discussion.

The basic insulating component of both specimens 7 and 8 was the core of Freon-blown, rigid polyurethane foam with a density of 2 pounds per cubic foot. The foam was furnace-cured in block form at 150° F for 4 hours, 230° F for 8 hours, and 300° F for 8 hours to eliminate trapped gases and constituents that are volatile at temperatures up to 300° F. Panels 0.4 inch thick were cut from the cured foam and encapsulated in a sealant covering of Mylar-aluminum laminate (0.0005 in. Mylar, 0.0005 in. aluminum, 0.0005 in. Mylar) referred to in reference 1 and herein as MAM laminate. These sealed panels were adhesively bonded to the model tank with a 6-inch-square glue line grid pattern as indicated in figure 2 and described fully in chapter VII of reference 1. Seam areas around the edges of the panels were filled with 0.30-inch-wide polyurethane-foam-filler strips and were sealed with a cover strip of MAM laminate as shown in figure 2. A layer of glass cloth was placed over the sealed-foam panels as a temperature- and erosion-resistant covering. The final component of the insulation system was a pretensioned constrictive wrap of fiberglass filaments that firmly secured the whole system to the tank. For a more complete description of the insulation system, see reference 1.

Specimen 7, consisting of four equal size sealed panels measuring 0.4 by 16.8 by 29.6 inches each mounted on the bottom of the model tank, is shown in figures 1 and 3(a). Specimen 8, consisting of a single sealed panel measuring 0.4 by 33.9 by 59.3 inches and a full-length unsealed foam buildup of the shape shown in figure 1, was mounted on the top of the model tank as shown in figures 1 and 3(b). The unsealed foam buildup simulated a fairing to include external wiring or conduit under the constrictive wrap without forming depressed or concave surfaces on the insulation.

Iron-constantan thermocouples were bonded to the glass cloth outer layer under the constrictive wrap in the patterns shown in figures 3(a) and (b). The pattern of figure 3(b) was duplicated with iron-constantan thermocouples between the sealed and unsealed layers of foam on specimen 8. Copper-constantan thermocouples were bonded to the outer surface of the tank on both top and bottom in patterns matching those shown in figures 3(a) and (b).

Test Setup

The insulated model tank (shown in fig. 3(c)) was sting-mounted at a negative 6° angle of attack in the test section of the 10- by 10-foot supersonic wind tunnel. This angle was considered to be an extreme condition for the launch trajectory. A blunt-body shock generator was mounted on the top (windward side) of the tank to simulate the presence of a large external protuberance. The shock generator could be retracted longitudinally to a position downstream of the model. The size and shape of the shock generator is shown schematically in figure 3(d). Liquid nitrogen was supplied to the model tank through insulated lines, and gaseous nitrogen boiloff was vented to the atmosphere outside the tunnel. The liquid level in the tank was monitored by liquid and gas sensors installed in the vent line. Automatic controls activated by these sensors maintained sufficient liquid nitrogen flow to keep the tank full at all times.

The airstream in the 10- by 10-foot wind tunnel was heated by a natural-gas-fired heater permanently installed in the bellmouth upstream of the supersonic nozzle. Vitiated airstream temperatures up to about 650° F were attained in this way. The wind tunnel can be operated either with or without this auxiliary heat input. Free-stream total temperature was measured by six high-recovery, aspirating-type thermocouple probes mounted on the forward edge of the model tank nose fairing (fig. 3(c)). Dynamic pressure in the airstream was computed from bellmouth total pressure measurements and the tunnel calibration constants. All temperature and pressure measurements were recorded by an automatic data recording system.

Test Procedure

Prior to starting airflow in the tunnel, the model tank and its associated plumbing system were filled with liquid nitrogen. Testing was begun at Mach 2.0 and progressed stepwise to Mach 3.5. Insulation surface temperatures were monitored and the heat input from the auxiliary heater was adjusted to obtain the desired insulation surface temperature. At each test Mach number, temperature and pressure data were recorded, first with an unheated airstream and then with a heated vitiated airstream. All data were obtained with the shock generator extended over the rear portion of specimen 8. Color motion pictures of the area influenced by the shock generator were obtained during or immediately following all test conditions. Following each run, visual observations were made through view ports in the tunnel wall to determine the general physical condition of the insulation system.

RESULTS AND DISCUSSION

Test Conditions

A summary of the test conditions covered in this investigation is given in table I. These test conditions involved maximum surface temperatures from 55° to 516° F, airstream dynamic pressures from 507 to 620 pounds per square foot and airstream Mach numbers from 2.04 to 3.54. A comparison of the test conditions of the current investigation and the predicted conditions of the assumed typical boost trajectory from chapter II of reference 1 is shown in figure 4. Data from the subsonic aerodynamic heating test in the turbojet engine exhaust stream and from the transonic-supersonic aerodynamic heating tests in a wind tunnel (chapter VI, ref. 1) also are shown in figure 4. In the Mach number range from 2.48 to 3.37 for the current tests with auxiliary heating, the environmental conditions of the tests approximate the predicted conditions over a portion of the assumed boost trajectory.

The time of exposure during this series of tests was extremely long in comparison with the exposure time associated with the typical launch trajectory. For the launch trajectory, the total time of exposure in the atmosphere (time period of the trajectory curve in fig. 4) is about 3 minutes (ref. 1). Because of the wind-tunnel-facility operating characteristics and the requirements of the data-recording system, time periods of from 2 to 5 minutes (see table I) were required to perform each test run. Approximately 15 to 20 minutes were required between successive test runs to change wind-tunnel Mach number or temperature level. As a result, accumulated exposure time at supersonic Mach numbers during the current investigation was about 2.4 hours and total operating time from startup to shutdown of the facility was about 5 hours.

Aerodynamic Effects on Insulation

Visual observations of the model tank through the viewing ports during tunnel operation did not reveal any damage to the insulation system other than discoloration. However, inspection of the tank and insulation after conclusion of the test runs showed that some damage had occurred in local areas. Except for these local damage areas, which are described in detail in this and the following sections, the insulation system successfully withstood the environmental conditions of the supersonic aerodynamic heating tests of this investigation.

The most obvious damage to the insulation occurred in the unsealed foam buildup (simulated conduit fairing) on specimen 8 immediately ahead of the blunt-body shock generator as shown in figure 5(a). This damage was due to impingement of the bow wave caused by the presence of the shock generator. The nature of this bow wave is shown schematically in figure 5(b). Associated with this bow wave is a very turbulent shock-boundary-layer interaction accompanied by large pressure and temperature gradients in a localized region immediately ahead of the shock generator. The effects of this bow wave became apparent in the discoloration of the outer surface of the insulation which was observed in the color movies taken after completion of run 5 (table I). Further deterioration of this portion of the insulation was obvious in the movies of subsequent runs. At the conclusion of run 8 (table I), the cumulative effects of this very turbulent flow field resulted in severe erosion and/or decomposition of the unsealed foam; discoloration and loss of resin had occurred in the glass cloth cover layer and the fiberglass constrictive wrap; however, these two components were still functioning properly (fig. 5(c)). By cutting away these outer coverings, it was revealed that at the center of the damage area (shown in fig. 5(d)) the thickness of the unsealed foam had been reduced from the original 0.6 inch to about 0.1 inch. There was no evidence of the effects of the bow-wave impingement being transmitted through the layer of unsealed foam to the underlying layer of sealed foam. In an actual vehicle application, damage of the nature shown in figure 5(d) would probably expose control leads that would normally be installed within such a foam buildup to dangerous environmental conditions. The use of a shallow-angle fairing around protuberances (similar to the 15° wedge shape reported in ref. 1) would avoid the formation of the bow wave, thus alleviating the extremely turbulent flow conditions and temperature rise and the accompanying damage to the insulation material.

Also apparent in figure 5(c) is a rupture in the seam area between the unsealed foam buildup and the corkboard insulation at the back of the model tank. This rupture is thought to be associated with both the impingement effects of the bow wave ahead of the protuberance and the difference in expansion rates of the corkboard and the foam. The rupture was confined to the unsealed layer and did not affect the insulating qualities of the system. Because the combination of foam and corkboard would not occur in a typical installation on a boost vehicle, this seam rupture was not considered to be a representative problem for the insulation system.

Aerodynamic effects on the insulation surface were apparent to a lesser degree at other points on the insulation system. A few isolated strands of the fiberglass constrictive wrap failed during the supersonic wind-tunnel tests; however, none of these strand failures were serious. Some discoloration and loss of resin in the constrictive wrap and in the fiberglass cloth were apparent on both of the test specimens, but no loss of structural integrity in the insulation system resulted.

A uniform longitudinal waviness on the outer surface of the unsealed foam of specimen 8 was observed at the conclusion of testing. The outer surface of the foam had taken a permanent set in a wave pattern with a pitch of about 3.75 inches and an amplitude of about 0.07 inch. This wave pattern was confined to the outer surface of the unsealed foam; there was no evidence of waviness on the bottom surface of the unsealed foam or in the underlying layer of sealed foam. There was also no evidence of surface waviness in the exposed foam panels of specimen 7 on the bottom side of the tank. The cause of this waviness could not be determined.

Nonaerodynamic Effects on Insulation

The major nonaerodynamic effect on the insulation actually was a result of a leak at a welded seam in the model tank rather than a direct result of the testing environment. A detailed review of this effect is in order, however, since previous experience has shown that this same effect can result from faulty sealing of the insulation system against the cryopumping of air during ground-hold prior to launch.

While inspecting the model tank in the wind tunnel immediately following the test operations, it had been observed that liquid nitrogen was dripping rapidly from the lowest point on the bottom of the tank. The leakage point was not immediately obvious, but the nitrogen flow seemed to be coming through the insulation seam area at the point of the dripping. It was also observed that there were areas in the sealed-foam panels on the bottom of the tank where the foam insulation was bulged and apparently cracked. Removal of the overlying fiberglass constrictive wrap and MAM covering showed that the foam had cracked in four local areas on three of the four panels of specimen 7 mounted on the bottom of the tank. Two of these local areas are shown in figure 6. Figure 6(a) shows the two bulged areas that were visible on the outer surface of the insulation system. Figure 6(b) shows cracked foam that was revealed after cutting away the constrictive wrap, glass cloth covering and outer MAM layer around the bulges of figure 6(a). Similar cracking of the foam insulation on a full-scale Centaur vehicle filled with liquid hydrogen for a simulated ground-hold test had been reported in chapter VIII of reference 1. The cracking of the foam cores reported in reference 1 were attributed to air that had been cryopumped between the insulation panel and the tank skin while the tank was filled with liquid hydrogen. During the warmup phase after the liquid hydrogen was removed from the full-scale tank, the cryopumped air expanded rapidly and caused pressure pockets to form beneath the insulation panels. Similar pressure pockets had been formed under the insulation panels during the current wind-tunnel tests; however, the source of the pressurizing gas was nitrogen leaking from the model tank. Subsequent investigation (after the model tank had been stripped of all the insulation covering and hydrostatically tested) revealed that the point of leakage was at a defect in the weld that joined the tank skin to the forward bulkhead. This defect was in the proximity of point A (fig. 1) on the bottom of the tank. Liquid nitrogen leaking through this weld defect ran between the tank skin and the insulation and some of the liquid nitrogen probably gasified while still under the insulation. This gaseous nitrogen caused pressure pockets to form between the tank skin and the insulation at any locations where breaks in the 6-inch grid pattern of the adhesive bond permitted entry. Pressurization beneath the insulation panels resulted in the cracking of the foam core as shown in figure 6. This damage to the foam core occurred only on the bottom of the tank.

The time period of exposure to the wind-tunnel environment in the present tests and the time period for warmup after the simulated ground-hold tests reported in reference 1 were both long compared with about 3 minutes of atmospheric dwell time during the typical launch trajectory shown in figure 4. From the test conditions imposed on this insulation system, it is not possible to predict accurately whether the short time of the launch trajectory could also generate serious pressurizing conditions if cryopumped air or leaking liquid hydrogen were present under the insulation panels. The potential danger from expanding gases is obvious, however. For this reason, the integrity of the sealant covering and constrictive wrap over the insulation is very important.

The tension in the constrictive wrap and the slight flexibility of the foam core assured that the inner surface of the insulation panels followed the contour of the tank. This was positively demonstrated by inspection of the insulation panels when they were removed from the tank after the tests. It had been observed prior to covering the tank with the test insulation that the tank surface was bowed outward (convex) between the lines of attachment to the internal ribs of the tank. These distortions were caused by warpage that resulted from the fabrication process. The distortions of the tank surface had an average amplitude of about 0.03 inch and a pitch of 6 inches (spacing of internal ribs). Stretching of the inner MAM layer of the insulation panels in local areas immediately above the tank ribs (the valleys or low points of the final tank surface configuration) was evident on samples removed from the panels. This stretching of the MAM showed that the compressive load generated by the constrictive wrap had forced the insulation panels to follow the slightly wavy surface of the tank. (The waviness of the outer surface of the unsealed foam, discussed previously, could not be related to the distortions of the tank surface; this waviness was confined to the outer surface of the unsealed foam only, and the pitch of the waves did not correspond to the spacing of the tank rib.)

GENERAL COMMENTS

A review of the results of all the aerodynamic heating tests to which this insulation system has been subjected will show that this system appears to be satisfactory for withstanding the aerodynamic environment that would be encountered during the assumed typical launch trajectory of a boost vehicle. The test specimens (specimens 7 and 8) used in the current investigation had been tested previously at transonic-supersonic conditions in the Lewis Research Center 8- by 6-foot transonic wind tunnel (ref. 1). The environmental conditions encountered during these previous tests are shown in figure 4. Insulation surface temperatures up to 212° F, dynamic pressures up to 1306 pounds per square foot, and free-stream Mach numbers from 0.56 to about 2.0 were imposed on the specimens during these previous tests. These test conditions exceeded the maximum dynamic pressure predicted for the assumed launch trajectory by about 50 percent. The total time of exposure in these tests at Mach numbers above 1.0 was about 1.5 hours. The accumulated exposure time in both series of tests (current and ref. 1) on specimens 7 and 8 at supersonic Mach numbers was about 3.9 hours. The total time that these specimens were subjected to airflow conditions in both series of tests was about 8 hours.

Specimens of the insulation system that were similar to specimens 7 and 8 but had not been subjected to the 300° F furnace cure described in the section APPARATUS AND PROCEDURE have been tested in the subsonic exhaust stream of a turbojet engine (see ref. 1). The environmental conditions encountered during these subsonic tests also are shown in figure 4. An insulation surface temperature of 690° F and a dynamic pressure of 1150 pounds per square foot were imposed on one of these specimens (specimen 4, ref. 1) for a period of 40 seconds. Severe erosion of the foam core occurred; however, the constrictive wrap and the glass cloth cover were still intact. Specimens 5 (sealed and unsealed foam combination) and 6 (sealed foam) of reference 1 were exposed to the environmental conditions shown in figure 4 for a total time of 82 seconds. Appreciable shrinkage of the unsealed-foam portion of specimen 5 and slight shrinkage of the exposed sealed portion of specimen 6 occurred as a result of this exposure. The constrictive wrap and glass cloth cover were intact on both specimens. Specimens 4, 5, and 6 were exposed at subsonic Mach numbers to combinations of dynamic pressures and insulation surface temperatures considerably in excess of those predicted for the assumed launch trajectory.

Data gathered during an actual launch of a Centaur boost vehicle have shown that the insulation surface temperatures measured during flight were lower than those temperatures predicted by the same analysis that was used to determine the trajectory temperature data shown in figure 4. (See ref. 2, fig. IX-11 and discussion.) This fact indicates that a further margin of safety may exist between assumed design conditions and actual conditions of the launch environment to which this insulation system would be subjected.

CONCLUDING REMARKS

In general, the constrictive-wrapped, sealed-foam external insulation system successfully withstood the environmental conditions of the supersonic aerodynamic heating tests at wind-tunnel free-stream Mach numbers between 2.0 and 3.5, insulation surface temperature up to 516° F, and dynamic pressures up to 620 pounds per square foot. Damage to the insulation due to the aerodynamic environment occurred only in a local area ahead of a blunt-body protuberance where a standing bow wave was formed. The nature of this damage was erosion and/or decomposition of the foam due to the extremely turbulent flow field and high temperature rise associated with the impingement of the bow wave. Consequently, protuberances should be streamlined to reduce the effects of shock-wave impingement.

At some of the high Mach number tests of this investigation, the dynamic pressure and the insulation surface temperature were in excess of the values of these parameters that would be expected in an assumed typical launch trajectory for similar Mach numbers. In addition, the total time of exposure to supersonic flow conditions was about 2.4 hours in these wind-tunnel tests compared with less than 3 minutes at supersonic conditions in the atmosphere during the assumed launch trajectory. From the results of these tests and other aerodynamic heating tests previously conducted on this insulation system, the system appears to be satisfactory for withstanding the aerodynamic environment that would be encountered during a typical launch trajectory.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 23, 1965.

REFERENCES

1. Lewis Research Center Staff: Sealed-Foam, Constrictive-Wrapped, External Insulation System for Liquid-Hydrogen Tanks of Boost Vehicles. NASA TN D-2685, 1965.

2. Lewis Research Center Staff: Postflight Evaluation of Atlas-Centaur AC-4. NASA TM X-1108, 1965.

TABLE I. - SUPERSONIC AERODYNAMIC HEATING TESTS

Run	Average free-stream conditions			Maximum[c] insulation surface temperature, °F	Approximate[d] time of exposure, min
	Mach number	Temperature, °F	Dynamic pressure, lb/sq ft		
[a]1	2.10	68	507	55	2
[b]2	2.04	236	527	191	5
[a]3	2.59	149	547	125	2
[b]4	2.48	375	620	312	5
[a]5	3.21	212	611	161	2
[b]6	3.06	521	594	433	5
[a]7	3.54	259	595	201	2
[b]8	3.37	649	558	516	5

[a]Without tunnel heater operating.
[b]With tunnel heater operating.
[c]Exclusive of bow wave area.
[d]Listed exposure times are for duration of test runs in which free-stream conditions were held constant at the values listed. Total exposure time in the wind tunnel at supersonic flow conditions was 2.4 hr.

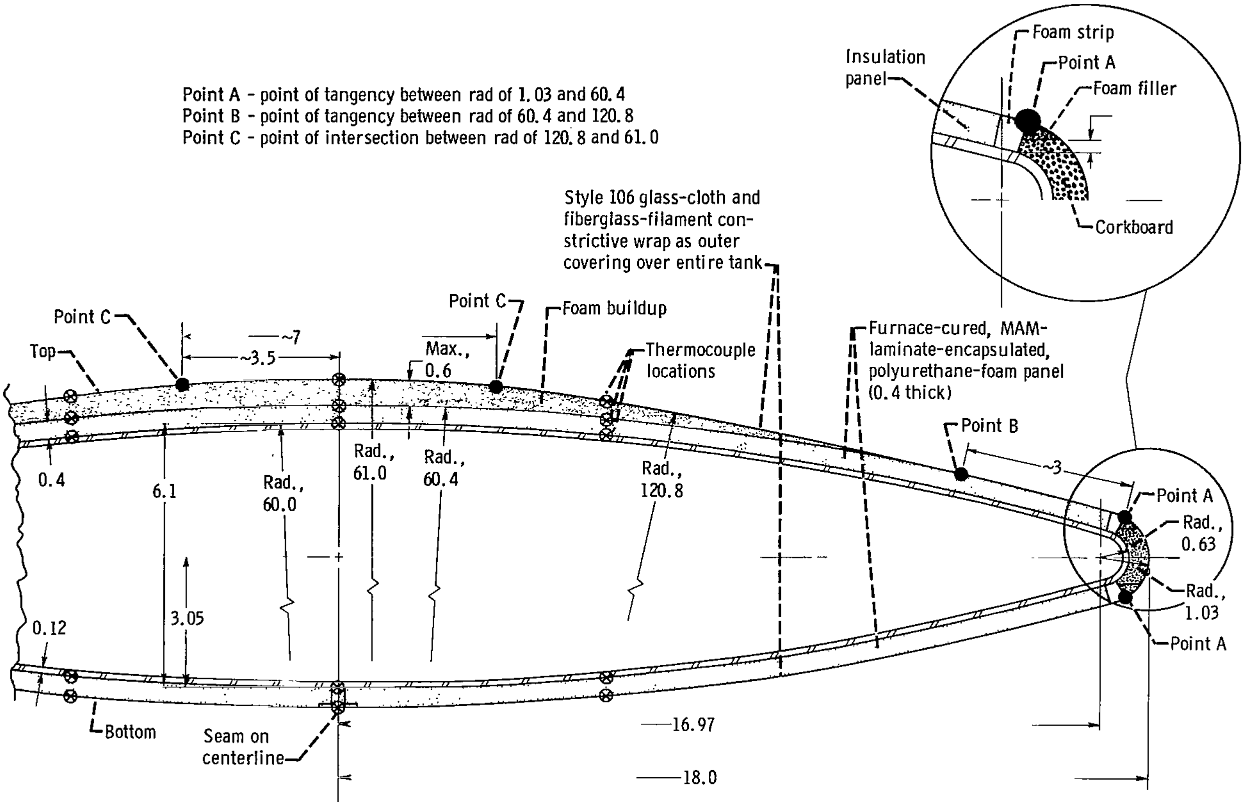
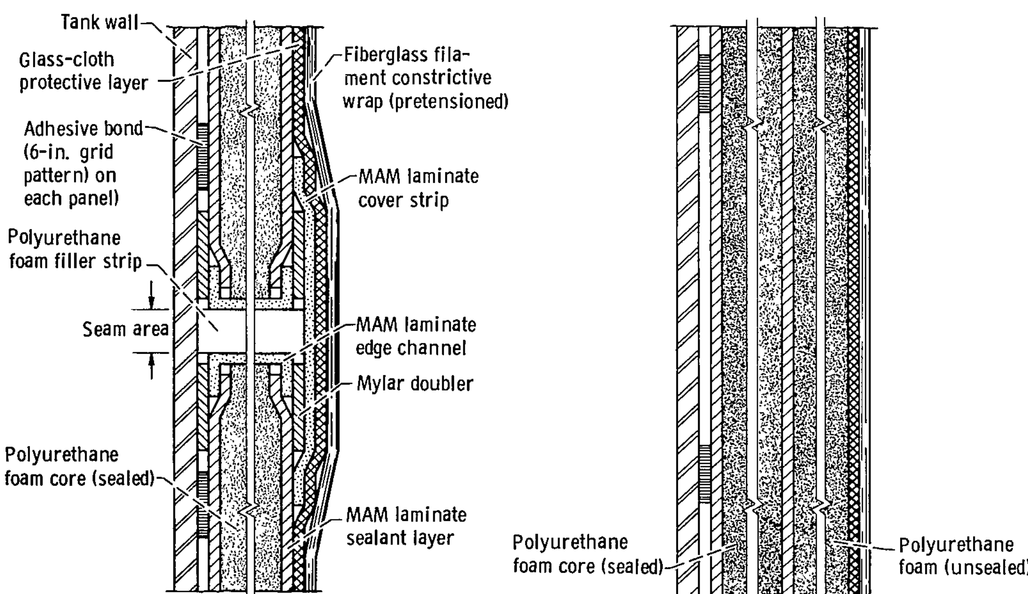


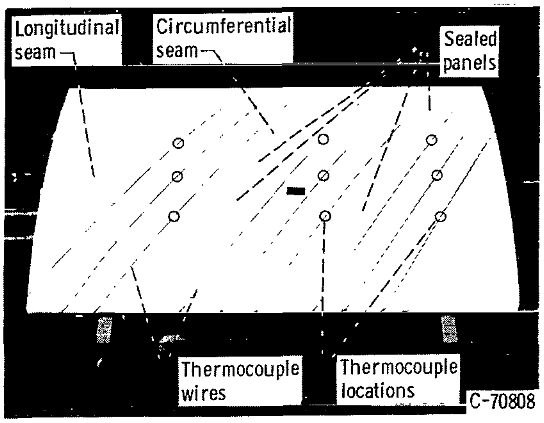
Figure 1. - Cross-sectional schematic diagram of model tank and insulation system used for supersonic aerodynamic heating tests. (All dimensions are in inches.)



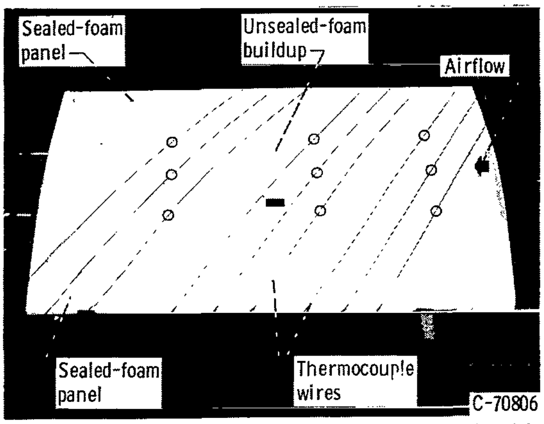
(a) Sealed panels (specimen 7).

(b) Combination of sealed and unsealed panels (specimen 8).

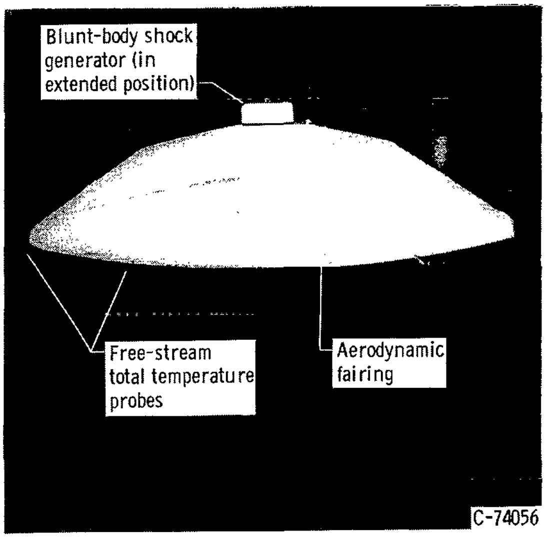
Figure 2. - Details of lightweight sealed-foam, constrictive-wrap insulation system. (Cross-sectional schematic diagram not drawn to scale.)



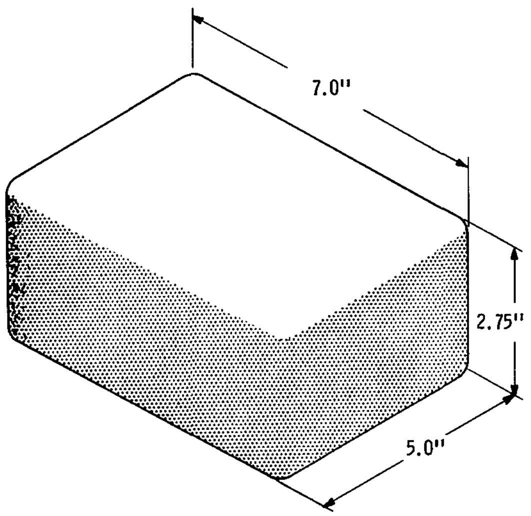
(a) Insulation specimen 7 mounted on lower surface of model tank. (Aerodynamic fairing not in place.)



(b) Insulation specimen 8 mounted on upper surface of model tank. (Aerodynamic fairing not in place.)



(c) Model tank with blunt-body shock generator and aerodynamic fairing installed in wind tunnel.



(d) Blunt-body shock generator.

Figure 3. - Apparatus for supersonic aerodynamic heating tests.

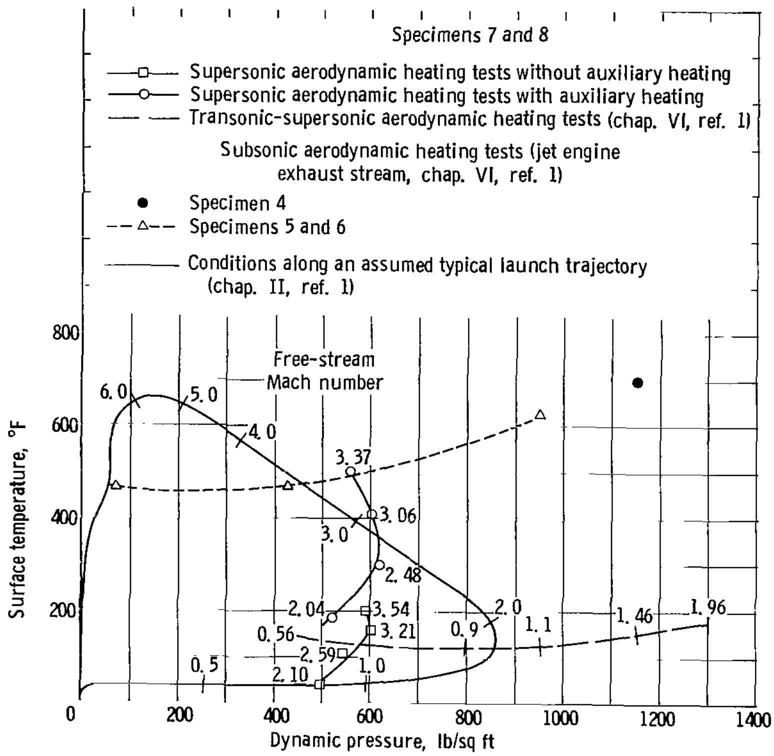
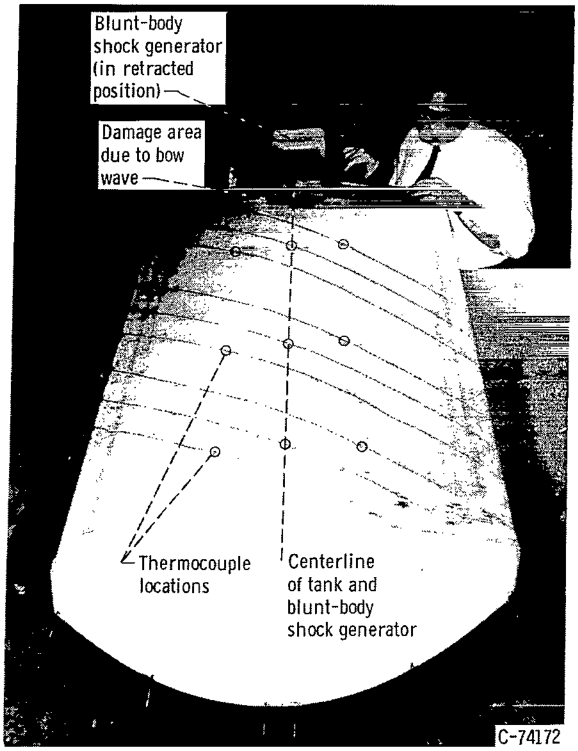
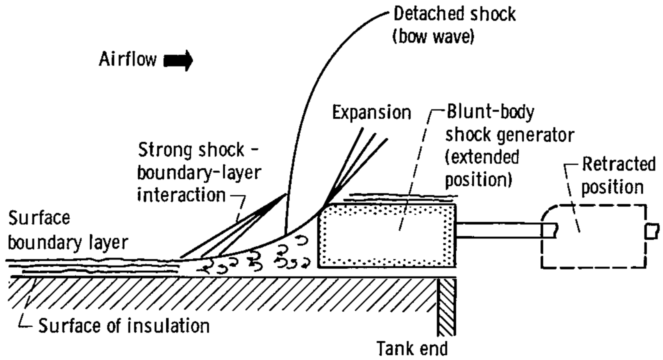


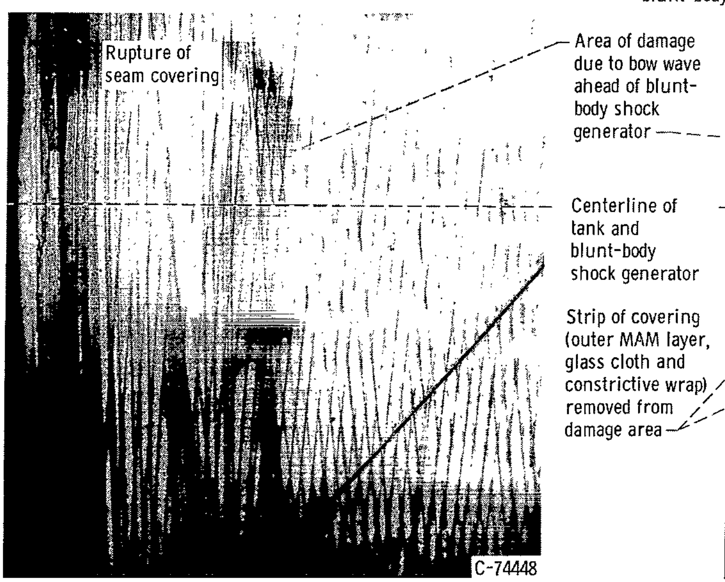
Figure 4. - Dynamic pressure and surface temperature on test specimens in supersonic aerodynamic heating tests.



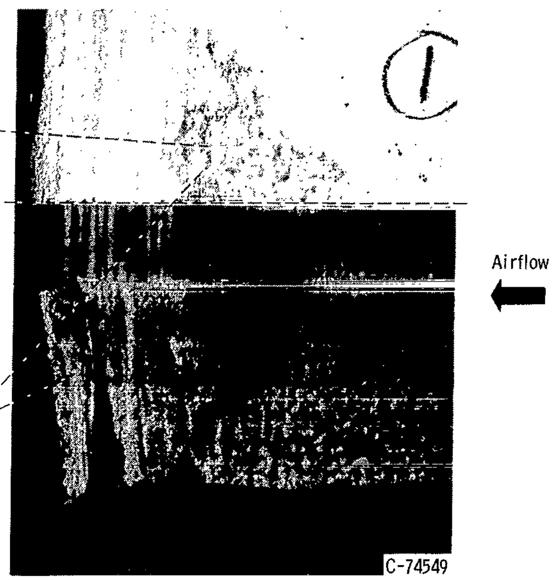
(a) Model tank after testing.



(b) Centerline schematic diagram of waveform generated in supersonic stream by blunt-body shock generator.

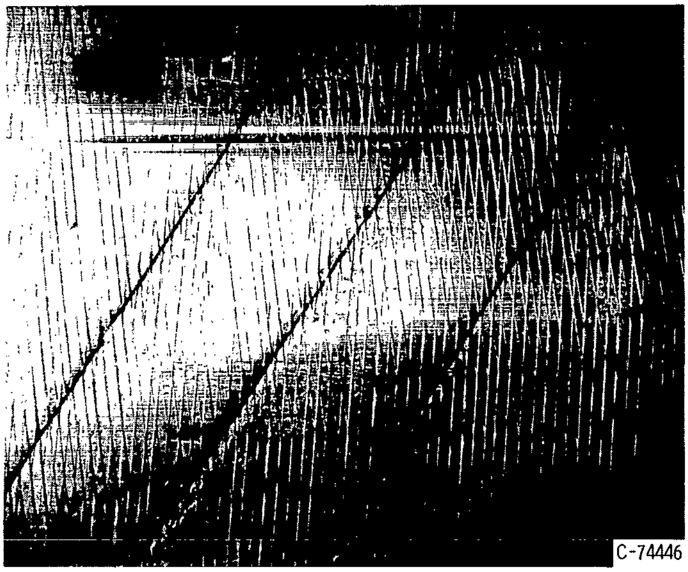


(c) Damage pattern on surface of insulation.

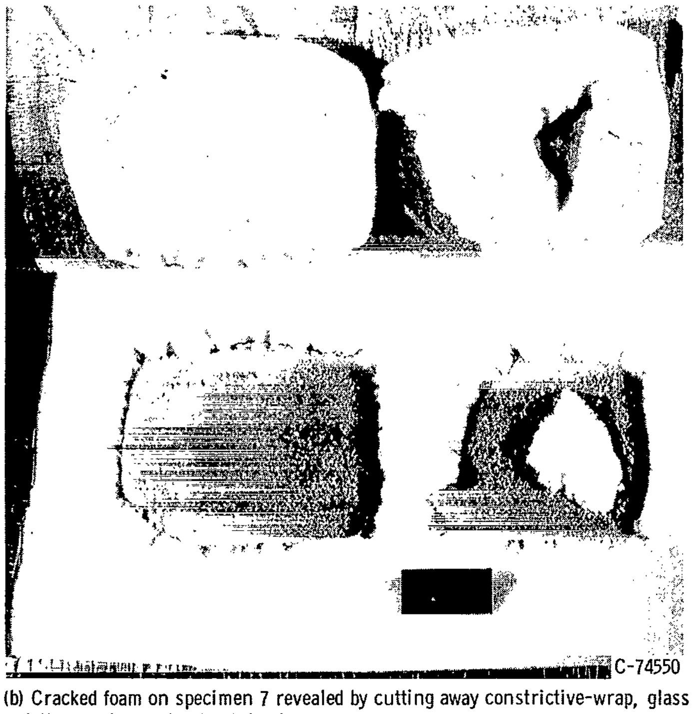


(d) Damage to unsealed foam.

Figure 5. - Damage induced on specimen 8 by bow wave formed ahead of blunt-body shock generator.



(a) Bulged areas on specimen 7 after test.



(b) Cracked foam on specimen 7 revealed by cutting away constrictive-wrap, glass cloth covering and outer MAM layer.

Figure 6. - Cracking of foam due to pressure pocket under insulation panel resulting from liquid-nitrogen leak.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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